HISTORIC AMERICAN ENGINEERING RECORD

TACOMA NARROWS BRIDGE

HAER No. WA-99

Location:	State Route 16 spanning the Tacoma Narrows of Puget Sound, Tacoma, Pierce County, Washington, beginning at milepost 7.28.
	UTM: 10/533620/5235420 10/534500/5234440
	Quad: Gig Harbor, Wash.
Date of Construction:	1951
Engineer:	Charles E. Andrew, Principal Engineer Dexter R. Smith, Design Engineer
Fabricator/Builder	Bethlehem Pacific Coast Steel Corp. John A. Roebling's Sons Co. of Calif.
Owner:	1952 to 1965: Washington Toll Bridge Authority. 1965 to the present: the Washington Department of Highways, since 1977, the Washington State Department of Transportation, Olympia, WA.
Present Use:	Vehicular and pedestrian traffic
Significance:	The Tacoma Narrows Bridge was the first suspension span constructed in the United States after its predecessor's failure in 1940 from wind-induced torsional oscillations. Research of design flaws in the first Tacoma Narrows Bridge led to the use of aerodynamic testing as a standard procedure in suspension span structural analysis, including studies for its replacement.
Historian:	Robert W. Hadlow, Ph.D., August 1993

History of the Bridge

The Tacoma Narrows Bridge is the first suspension bridge in the United States built after the disastrous 1940 failure of its predecessor. When constructed, both were the world's third longest suspension bridge, behind only the Golden Gate Bridge and George Washington Bridge for length of suspended span. But unlike its predecessor, the second Tacoma Narrows Bridge's design included several features that made it unaffected by the wind forces that destroyed the first structure. It marked a new beginning for the structural engineering field in this type of construction. In studying the design flaws in the first structure to fathom the reasons for its failure, researchers looked for ways to more clearly understand the physical characteristics of suspension bridges. The fruits of their research--their greater knowledge of how wind forces acted on bridge members--aided in better designing of all future suspension bridges.

The Tacoma Narrows was the most logical crossing for a bridge between the eastern shores of Puget Sound and the Kitsap Peninsula. Tacomans had dreamed of spanning this narrow point because it gave them easier access to the Olympic Peninsula and opened a new commercial market of Kitsap County residents who depended on nearby Bremerton shops for their goods and services.[1]

In 1932, a local civil engineer, Elbert M. Chandler, organized the Tacoma Bridge Company which hoped to raise at least $3.5 million to construct a Narrows bridge. With Pierce County unable to acquire construction dollars, Chandler applied to Herbert Hoover's Reconstruction Finance Corporation, a depression-era public works agency, for funds, but it flatly denied his request for $3 million. The RFC believed that expected toll revenues could not pay for the project. Nevertheless, in early 1933 the U.S. Army Corps of Engineers approved Chandler's plans for a bridge across the Narrows.[2]

Chandler found even less cooperation with Franklin D. Roosevelt's Public Works Administration, under Harold Icke's direction. Washington Senator Harold Bone and private citizens pressed the PWA to support a Narrows bridge project, but only in the late 1930s when the Washington State Legislature created the Washington Toll Bridge Authority to finance and operate a floating bridge across Seattle's Lake Washington and a suspension bridge across Tacoma Narrows did the federal agency take notice. In June 1938, the PWA approved a grant for about $3 million--half of the estimated $6.4 million construction costs--with the RFC providing the remainder by purchasing state revenue bonds.[3]

Clark H. Eldridge, bridge engineer for the Washington Department of Highways, and his staff had designed a bridge for the crossing, but it was abandoned in favor of a less expensive plan. Eldridge's bridge was a two-lane suspension structure with 25' deep stiffening trusses on either side of the roadway to lessen the structure's susceptibility to the strong Narrows winds. Projected construction costs for Eldridge's bridge were $11 million. Eastern engineers believed that these were too high and recommended to the PWA that the structure be completely redesigned. Well-known suspension bridge engineer Leon Moissieff was called in to prepare new plans, and the $6.4 million financial package was arranged.[4]

Construction began on the Narrows bridge in late November 1938, but only after the revised pier plans prepared by the firm of Moran and Proctor were rejected as too costly, and Eldridge's original version substituted in their place. Moissieff's new design for the superstructure was retained. Its cost-saving measures included changes in the floor system and deck that kept the price under $6.4 million. The Pacific Bridge Company of San Francisco became the lead contractor on the project with Bethlehem Steel Company furnishing and erecting the steel and wire.[5]

Moissieff's Narrows bridge consisted of a two-lane 5,000' suspension structure--two 1,100' side spans and a 2,800' main span. Its road deck measured 26' curb-to curb. In addition, it had 5' sidewalks. The towers ran 425' above the piers and were of batter design, 50' at their bases tapering to 39' at their crowns. Moisseiff wrote in August 1939 that the deep and swift moving Tacoma Narrows' waters dictated that a long-span suspension structure was the only practical bridge to span the channel. His design also reflected results of traffic surveys which recommended only two traffic lanes. But to some, Moissieff's bridge appeared Oz-like with its thin steel ribbon spanning between two delicate towers, their height exaggerated by their batter design.[6]

Moissieff designed the suspension span within these constraints and the spending limitations. Moreover, he also created the Tacoma Narrows structure within the framework of deflection theory. That is, the idea that the dead load of a suspension structure substantially moderates structural distortions under live load. He believed that "trusses of great stiffness reduce but little the deflections of [a] bridge." Moisseiff added, "Contrary to the behavior of ordinary girders and trusses, the vertical deflection of the bridge is not proportional to the moment of interia of the truss." Instead, he believed that it was dependent on structural weight and proportion. Moisseiff concluded that he could reduce truss depth without adversely affecting bridge stiffness. He carried this theory further by postulating that the use of shallower stiffening trusses naturally led to plate girders, which he believed offered "many structural advantages for connections and fabrication" and "presented a simple and good appearance and [were] easy to maintain." Finally, he believed that cables had the ability to control and supply stiffness to a suspension bridge. By flattening the catenary of the cables to a modified parabola he could increase the rigidity of the bridge's polygon, again reducing the stiffening girder's depth.[7]

Moisseiff designed his Tacoma Narrows Bridge with a length-width ratio of 72 to 1. He used 8' girders with a 1/2" web plate. They were stiffened with three longitudinal "zees" on one side of the web and vertical channels on the other side. The plate thickness was 1-7/8". He saw this girder as less important as a beam for distributing live-load and limiting deflections and more important as a component of the structure in resisting lateral wind forces which he saw as most significant in long, narrow spans that had high wind stresses. He promoted his web plate design as more economical than others because his stiffening channels afforded a reduction in material. Moisseiff believed that he achieved the structure's stiffness by a 232' versine of the cables.[8]

Moisseiff saw his bridge as an economical, yet sturdy, structure that could withstand any type of wind force. He believed that it was the natural beneficiary of a long progression in "modern suspension bridge construction." These included the Manhattan Bridge, with the first application of deflection theory to a span; the George Washington Bridge, with a design acknowledging the extreme stiffness of the cables themselves; and the Bronx-Whitestone Bridge, with the first use of shallow plate girders as stiffening members in a long-span suspension structure. Moisseiff disapproved of the view that most engineers held concerning length-to-width ratios for long-span suspension bridges. In 1933, his experimental verification of his theories gave him what he believed was accurate data and the result was the ability for engineers to "plan long spans more boldly," and "more economically so that they become practicable.[9]

Construction on the Tacoma Narrows Bridge was completed on 1 July 1940. When it opened on the 4th of July 1940, the Washington Toll Bridge Authority boasted of its modern design and its uniqueness and compared it to the Golden Gate Bridge (at that time the largest suspension span in the world). The piers were founded in 200' of tidal water rushing at 8.5 miles per hour. This was nearly double the depth for the Golden Gate Bridge's pier caissons, and those had been unprecedented at the time of their construction, less than one-half decade before the Narrows bridge. The airy feature of the Tacoma structure was attributed to its ribbon-like width-to-span ratio of 72-to-1 which far exceeded the California bridge's of 45-to-1.[10]

The public had genuine affection for the Tacoma Narrows Bridge. It was a record setting span, with an advanced structural design. One bank in Tacoma saw the opportunity to capitalize on its construction by erecting a billboard nearby that read "Safe as the Narrows Bridge." An insurance agent who wrote a policy on the structure for the Toll Authority pocketed the premium, knowing that he had made an easy swindle. But even before the bridge opened to an overwhelming number of motorists, it was exhibiting characteristics of structural instability. Workers who were placing the concrete deck noticed early on that the suspended span tended to undulate with even the slightest breeze. They often became seasick when the floor rose and fell a range of nearly three feet. The bridge became some sort of novelty ride as motorists were eager to experience her rippling motion. Many also found that oncoming automobiles appeared to vanish behind hills as the waves moved through the structure. Traffic over the bridge--"Galloping Gertie"-- during its first two weeks was double the engineers' predictions.[11]

What seemed akin to a carnival ride for motorists was a serious concern for the Washington Toll Bridge Authority. At its request, the University of Washington engineering department began a study of vertical oscillation in the bridge's deck, hoping to discover a means to reduce the movements. Frederick B. Farquharson, a professor of civil engineering, led the investigation primarily experimenting with a dynamic model of the bridge in a wind tunnel. In the meantime, hydraulic buffers were installed at the towers to check longitudinal motion. Diagonal cable ties connecting the suspension cables to the stiffening girders were placed at the main span's center with the hope also of minimizing longitudinal movements. But despite these measures, the structure continued to undulate in vertical motion with moderate amplitudes.[12]

After completing preliminary wind tunnel tests with a scale model of the bridge, Professor Farquharson suggested that several additional modifications be made to the structure to possibly cure its susceptibility to wind. He placed tie-down cables in the side-spans, attaching them to concrete anchorages. He also planned to streamline the girder's shape, believing that it's large flat surfaces contributed to the oscillating movements, either by drilling a series of holes along the plate girders to let the wind pass through them or installing fairings along them to deflect the wind around them. Farquharson's side-span tie-downs were installed in early October 1940, but they snapped during the first windstorm. He never had a chance to modify the girders.[13]

The bridge had pronounced vertical oscillations even in the lightest winds. It was not unusual for suspension spans to exhibit some susceptibility to them, but where the Tacoma Narrows bridge differed from other structures was that the movements did not die down, and there was no correlation between wind strength and movement. Because of this, Farquharson closely monitored the bridge, measuring wind velocities and noting the shape of wave motions in the structure. He even filmed them for future study. During the morning of 7 November 1940 sustained winds of 38 miles per hour were whipping through the Narrows. By 10:00 a.m. these had increased to 42 miles per hour. Professor Farquharson captured the bridge bouncing, with the deck rising and falling in nine waves at 38 times per minute with a 3' double amplitude. But suddenly the frequency changed, slowing to 12 cycles per minute. The action also turned from a rhythmic vertical motion to a two-wave torsional movement with the center span's mid-point at rest. One cable and its stiffening girder developing a lag phase movement with its counterpart. The deck began to twist and roll violently. As the frequency decreased, the motion became greater until the deck had gone from the earlier 3' to 28'. One minute one edge of the roadway was 28' higher than the other, and the next it was 28' lower. It tilted 45 degrees from the horizontal one way, then 45 degrees the other way. David Steinman, a preeminent suspension bridge designer wrote after viewing Farquharson's film of the oscillations that "it was difficult to realize that the girders were made, not of rubber, but of structural steel having a modulus of elasticity of 29,000,000 pounds per square inch."[14]

At 11:00 a.m., a 600' section of roadway 300' west of the center span's midpoint fell away, unzipping the girders from the floor. The motion continued. In less than ten minutes the whole span fell into Puget Sound. This caused the two 1,100' side spans to sag violently, 45' below normal elevation. The towers with their unbalanced loads deflected over 12' toward the side spans and buckled plating. "The torn, tangled, twisted stub ends of steel work sticking out from the towers," Steinman wrote, "were all that was left of the main span." A bridge that had taken years to plan and build became in a few short hours little more than a mass of twisted metal and broken concrete.[15]

Almost immediately speculations abounded about the failure's cause. The state of Washington and the Public Works Administration organized investigatory boards. Meanwhile, Professor Farquharson continued his wind tunnel tests, concluding early on that the bridge went into "intense resonant oscillation under the cumulative effect of undampened rhythmic forces." The bridge failed because of its lightness and built-up wind pressures against the eight-foot plate girder and the solid deck.[16]

In their synthesis of the case, Matthys Levy and Mario Salvadori in *Why Buildings Fall Down* wrote that when it collapsed, the Narrows bridge acted like many failed eighteenth- and nineteenth-century suspension structures. Principally, their length-to-width ratios were very great which, in part, permitted a twisting motion before they came apart. They were inherently weak in torsion, particularly when they lacked stiffening necessary to prevent longitudinal "galloping." Steinman believed that twentieth-century engineers had not learned from their predecessors' mistakes. While their designs accounted for dead load, live load, temperature, and static wind load, they did not allow for wind load's dynamic effect.[17]

On the morning of the bridge failure, with a gale between 35 to 42 miles per hour, the wind pressure was only five pounds per square foot. While Moisseiff designed the Narrows structure for a static wind pressure of 50 pounds per square foot, the wind it experienced acted as a dynamic force. The steady wind's effects on the structure produced a fluctuating resultant force that automatically synchronized in timing and direction with the bridge's harmonic motions. This progressively amplified the motions to destructive levels. The Tacoma Narrows Bridge's inherent weakness and susceptibility to these winds lay in its shallow stiffening girders and its narrow roadway. Steinman believed that Moissieff alone was not to blame for the Tacoma Narrows collapse, instead it was the structural engineering profession because it "had neglected to combine, and apply in time, the knowledge of aerodynamics and of dynamic vibrations with [developments in their field]."[18]

Theodore von Kármán, who had pioneered wind tunnel analysis at the California Institute of Technology, argued that the bridge deck's aerodynamic shape was a more important factor in its failure than its lightness and flexibility. Von Kármán suspected that the bridge had experienced vortex shedding, a condition where objects like airplane wings or bridge decks displace air flowing around them, forming eddies or vortices, which may induce vibration in the object. He believed that wind flowing over Moisseiff's solid girder side plates created shedding that when combined with the flutter and resonance already present in the deck produced the violent oscillations that caused the catastrophic failure.[19]

Von Kármán worried that the Washington Toll Bridge Authority planned to rebuild the bridge with simply a huskier version of the original structure because he believed that this would not prevent a repeat of the bridge's disaster. Von Kármán's wind tunnel tests on scale models in California and Farquharson's at the University of Washington showed that a replacement structure similar in design to the original span but with a widened deck and deepened stiffening girder would not necessarily lessen its susceptibility to torsional oscillations. Even the Bronx-Whitestone Bridge, a plate girder stiffened suspension bridge that Moisseiff designed before building the Narrows bridge, experienced resonant movement. Von Kármán advised instead for the replacement structure that it have an open-truss stiffening system and ventilation grates between traffic lanes to help equalize wind pressure above and below the deck and avoid vortex shedding. The engineering community in the early 1940s seemed reluctant to openly accept Theodore von Kármán's vortex shedding explanation, but structural comparison between the Tacoma Narrows Bridge, and all succeeding American suspension bridges shows that aerodynamicity played a significant role in their design. Research in the early 1990s suggests a greater public acceptance of von Kármán's 1940s findings.[20]

The second Tacoma Narrows Bridge, built from 1948 to 1951 incorporated many design elements directed at preventing the dangerous twisting and galloping motions that destroyed its predecessor. These included open trusses rather than shallow plate girders for greater stiffness and, combined with deck grating between traffic lanes, less wind resistance. A larger roadway width-to-span length increased twisting resistance and reliable damping mechanisms prevented the indefinite progressive increase in aerodynamic oscillation magnitude seen in the earlier bridge. The world structural engineering community learned from the events in Tacoma, Washington, in November 1940. It would be nine years until the American bridge-building community again attempted a suspension span. It was the second Tacoma Narrows Bridge.[21]

Design and Description

The Washington Toll Bridge Authority began considering designs for the replacement Tacoma Narrows Bridge almost immediately after the first structure failed. Professor Farquharson's research at the University of Washington and Theodore von Kármán's studies at the California Institute of Technology continued, in part, to understand the reasons for the Narrows bridge failure, but just as importantly so that the profession might better fathom suspension bridge aerodynamics' complex nature. One immediate beneficiary of their work was the new design team that the Toll Bridge Authority created to plan Galloping Gertie's replacement.[22]

In 1941 Charles E. Andrew, as consulting engineer for the Authority, chose Dexter R. Smith, a chief design engineer loaned from the Oregon State Highway Commission Bridge Department, to plan the new structure. Smith's career began in the 1910s as a faculty member with the Oregon Agricultural College in Corvallis where he taught structural engineering. He was a colleague of Conde B. McCullough (Oregon State Bridge Engineer from 1919 to 1936), whom he followed to the OSHC in the late 1920s as a principal bridge designer. He achieved a reputation as a top structural specialist. Smith's greatest design contribution to Oregon bridge building was a large reinforced-concrete deck arch used repetitiously in approach spans in the state's mid-1930s $6 million bridge construction program along the oregon Coast. But he also worked closely with McCullough, a noted short-span suspension bridge expert, in researching suspension bridge design in the late 1930s and early 1940s.[23]

Smith and his colleagues collaborated with Farquharson's research group at the University of Washington. Their design criterion for the replacement structure called for a practical plan that provided the least wind resistance with a minimum of large flat surfaces. They believed that they could achieve this by using deep, open stiffening trusses with trussed floor beams instead of plate girder stiffening members and beams. They hoped that with shallow truss members they might avoid creating any large flat surfaces that led to the first bridge's wind instability. Instead, they believed, the truss form-'s openness would break up wind, reducing its destructive power.

Smith's team in the most basic sense understood the need to overcome wind resistance in the replacement structure's design. Farquharson's researchers had studied the original structure reaction to wind and had created a dynamic scale model of it which they wind-tunnel tested. Von Karman postulated that airplane wings and bridge decks were similar in the sense than certain designs were more susceptible to wind effects, but he acknowledged further research using dynamic scale models was needed to better understand this phenomenon. The result was that Smith's team worked closely with Farquharson's group in studying bridge design models both from the pure research aspect and the application to creating the second Tacoma Narrows bridge. They were pioneering the field of bridge aerodynamics.

Smith's group began with Farquharson's observations of Galloping Gertie, for there were no dependable records of wave movement on other suspension spans. No bridge other than the first Tacoma Narrows bridge had been studied both through visual observation and wind tunnel analysis. Farquharson's data from both investigations were the basis for continued research with the hypothesis that if a dynamic scale model of a design proposal could successfully complete rigorous wind tunnel testing, then, with confidence, engineers could construct a full-size version at the Narrows site.

Farquharson's team constructed a 1:50 scale model of Smith's design with materials that made it a true dynamic representation. Their data gathered from tests proved that the bridge was much more stable than the failed structure. Knowing that the Narrows's winds were, in general, horizontal, they subjected the model to forces with angles between two degrees upward and five degrees downward. It exhibited complete stability. Nevertheless, researchers feared that crosswinds, often blowing upward at six to eight degrees toward the Narrows' high west shore might induce torsional oscillation in the new design. Tests proved their theories correct, and slight modifications to the deck truss helped minimize the movement. Still, they sought ways to nullify the wind's effect and chose to fit the model's solid deck with a series of longitudinal grates to permit freer air flow. The design change, first promoted by Theodore von Karman years before, proved the cure, with only minute, and, in the researchers minds, an insignificant amount of residual torsional movement.[26]

Smith's and Farquharson's teams were not satisfied with their ability to nearly eliminate torsional and vertical movements in their design. They understood that all bridges have the capability of damping dynamic energy, but attempts to quantify this idea was, by the 1940s, minimal. Damping helped control wave amplitudes, and they hoped to enhance their design's natural damping ability with mechanical devices. The first was a double lateral bracing system in the stiffening truss. It increased torsional frequency motion and torsional stiffness. The second was an assortment of several cylindrical hydraulic shock absorbers used at three points in the structure: coupling the top of the stiffening truss at mid-span with the suspension cables, connecting between the top chords of the main span and side span stiffening trusses, and extending as outriggers from the trusses' bottom chords to the towers.[27]

The result of research on design possibilities was the following structure for the Tacoma Narrows. Reading west to east, it was:

one 162'-6" west anchorage
three 150' steel deck girder approach spans
one 1,100' cable suspended steel side span
one 2,800' cable suspended steel main span
one 1,100' cable suspended steel side span
one 45'-2-1/2" reinforced-concrete T-beam approach span
one 42'-5" reinforced-concrete T-beam approach span
one 45' reinforced-concrete T-beam approach span
one 45' reinforced-concrete T-beam approach span
one 185' east anchorage and toll plaza

length of suspended spans, 5,000'
deck width, curb-to-curb, 46'-8 1/8", including
-four 9' lanes separated by 2'-9" slotted wind grates and 1'-7" wind grates separating the roadway from the sidewalks
two 3'-6" sidewalks, one on each side of roadway
width between suspension cables, 60'
two 20'-1/4" diameter main cables

The suspended spans' deck configuration includes a 33'-deep riveted-steel Warren stiffening trusses with double lateral bracing. Deck beams are 11'-deep trusses placed 6 feet apart. I-beam deck stringers rest on the beams. Finally, a 6-3/8" thick reinforced-concrete deck slab with wind grating sits atop the stringers. Construction began on the $11 million second Tacoma Narrows bridge in April 1948 with Bethlehem Pacific Coast Steel receiving a contract for steel fabricating and erecting. John A. Roebling's Sons spun the cable. A $14 million bond issue financed the project with the Washington Toll Bridge Authority operating and maintaining the structure until bond obligations were paid.[28]

Work on the second Tacoma Narrows bridge began first with the piers that were constructed in 1938-39 for its predecessor. They had received minimal damage during Gertie's collapse. While the state collected $4 million in insurance compensation for the first bridge and salvage rights to its remains, it left the piers, minus their towers, and the west approach span in place. Some skeptics feared that the original piers could not bear additional foundatian pressures from the-more massive replacement span. Others believed that a series of earthquakes that shook the Puget Sound area since 1938 had weakened them. 8Oth groups' assumptions were incorrect. The quakes inflected no damage on the piers, and while weighing 160 percent more than the old structure, the new bridge's superstructure design only increased the dead load pressure on the piers by 6 percent. The new towers, with wider bases, actually created a better, more even load distribution.

The channel piers used for both Tacoma Narrows bridges consisted of cellular reinforced-concrete built upon caissons sunk to the Narrows' floor. On these were poured concrete caps and pedestals for the steel tower legs. Contractors in March 1939 began pier construction by floating sections of caissons from Seattle supply yards to the Narrows, where they were anchored, each with twelve 570-ton concrete weights. The caissons, nearly 66' x 119' consisted of steel trussing and girders arranged within wooden sheathing and finished on the lower portion with a sharp metal cutting edge. Once the pontoon was positioned to hover over its designated location, concrete was poured and it sunk under its own weight to a point-where a 12' wooden hull was erected on its top with steel framework and partitions and then it was concreted. The process, which took three months, was repeated in 12' increments until the bottom section of the pier, with its sharp-cutting edge reached the Narrows' sea floor. Then, boards in the caisson's bottom section were removed and buckets scooped away mud and gravel, pulling it up through the pier's hollow concrete cells to the of surface. Bit by bit, the caisson sank to the Narrows' firm bedrock foundations. Once this process was completed, the workers placed concrete caps over the piers and the original Tacoma Narrows bridge's 425' steel towers were erected.[30]

The piers sat for nine years after Galloping Gertie's collapse until construction began on her replacement's towers. The new design called for twin steel legs, 60' on center, resting on the piers. The original pedestals accommodating the first bridge's 50' batter towers were not wide enough for the new structures. While the first bridge's road deck was designed for two traffic lanes, its replacement's was wide enough for four traffic lanes. In addition, studies subsequent to the first bridge's destruction found that during Gertie's short existence salt water corrosion was evident on her tower legs. Designs for the replacement bridge called for not only erecting new, wider pedestals, but also lengthen them by 18' to raise the bottom of the new tower legs above the upper limit of salt spray. For these two reasons, the towers rose 58' higher than those on the first Narrows' bridge.[31]

Tower legs consisted of four cellular columns arranged in such a manner to form a fifth hollow core. Fears of high winds destructing the flexible tower legs before cables and deck trusses acted to stabilize them prompted designers to erect temporary outriggers for added support. Chicago booms attached to the completed towers' top cross-bracing hoisted and placed a 28-ton cast-steel cable saddle on the top of each leg[32]

In the meantime, Galloping Gertie's anchorages, spaced 39' apart, were retrofitted to accommodate the new bridge's 60' separation between cables. Portions of the original structures were reused as the cores of new, heavier and wider 54,000-ton anchor blocks constructed to resist the new structure's increased cable load. With the piers and anchorages modified to accept the new bridge's dimensions, construction began on the towers and suspended spans.[33]

With the towers and saddles in place, workers spun the 20" main suspension cables. The new, wider anchorages included new eyebars imbedded 62' into the new concrete. Each main cable was composed of 19 strands consisting of 458 No.6 gauge wires. Each strand was continuous from anchorage to anchorage, making loops at the eyebars' 26" diameter shoes. Once cables were spun, crews hung deck suspenders consisting of four 1-3/8" wire cables.[34]

When Galloping Gertie's plate stiffening girder and deck were erected, they were preassembled in sections, hoisted from barges and riveted into place. Because of its composition, the stiffening truss system on the second Tacoma Narrows bridge was more easily assembled on the job from shop-fabricated components. Two crews of riveting teams and traveller operators worked from the tower piers to the center of the main span, while two other crews worked from the piers to the shore.[35]

The procedure for erecting the deck system began with placing the top and bottom chords and their diagonal bracing. Then, the pretrussed floor beams were positioned between the chords. Deck stringers were laid lengthwise on top of the beams. Crews pinned the members in place, and behind them came the riveting gangs. As the process moved along, other workers followed behind attaching deck suspenders running from the main cables to the stiffening trusses with non-corroding zinc jewels. With the deck system completed, the reinforced-concrete roadway was poured and the wind grating was installed. Finally, crews attached the mechanical damping devices. The bridge opened for traffic on 14 October 1950.[36]

The Washington Toll Bridge Authority operated and maintained the Tacoma Narrows Bridge until 14 May 1965, when Governor Daniel Evans signed a bill at the bridge's toll plaza to signify an end to toll collecting thirteen years ahead of schedule. Since its opening in 1950, heavy traffic brought in more than $19 million in collections. From then, the Washington Department of Highways, and its successor the Washington State Department of Transportation, owned and maintained the bridge.[37]

Repair and Maintenance

During its history, the Tacoma Narrows Bridge has been subjected to several wind storms that required closing the structure to truck traffic to avoid having vehicles blown into oncoming traffic. Not once was the bridge closed because of bridge deck oscillations. In addition, there are no visual or instrument recordinqs of deck oscillation that were considered extraordinary. An earthquake in 1965 caused some minor damage to the bridge.[38]

An Olympia-based engineering consulting firm completed a comprehensive inspection of the Narrows bridge in 1983 and found that the suspender ropes had stretched over time, with those near the towers increasing bearing reactions in the towers as they shed their load. In addition, the main towers' east wind shoes were locking, increasing stress in the tower legs, and hydraulic dampers were not functioning because of deteriorated seals. [39]

In a subsequent evaluation, in 1991, relying heavily on advanced testing techniques including computer modeling, the Olympia firm concluded that the stretch in suspenders noted in 1983 was insignificant. It recommended that further studies were warranted involving a comprehensive dynamic investigation of the bridge, taking advantage of recent advances made in understanding aeroelastic phenomena. It also proposed a seismic risk analysis to determine the structure's ability to survive powerful earthquakes.[40]

The bridge has proved an important link between Tacoma and the Kitsap Peninsula. Traffic volume has steadily increased from an average of 16,339 vehicles per day in 1967 to an estimated 87,000 vehicles per day in 2000. Planners may consider alternatives to improve traffic flow across the narrows, including modifying the bridge to accommodate several more traffic lanes, or constructing an additional bridge.[41]

Data Limitations

Research resources are abundant on this bridge. The best repositories are the Washington State Department of Transportation Library, and the Washington State Library, both in Olympia; WSDOT's Bridge Preservation Section files; and articles about both bridges in professional engineering journals, found in most university research libraries.

Project Information

This project is part of the Historic American Engineering Record (HAER), National Park Service. It is a long-range program to document historically significant ehgineering and industrial works in the United States. The Washington State Historic Bridges Recording Project was co-sponsored in 1993 by HAER, the Washington State Department of Transportation (WSDOT), and the Washington State Office of Archeology & Historic Preservation. Fieldwork,-measured drawings, historical reports, and photographs were prepared under the general direction of Robert J. Kapsch, Ph.D., Chief, HABS/HAER; Eric N. DeLony, Chief and Principal Architect, HAER; and Dean Herrin, Ph.D., HAER Staff Historian.

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SELECTED BIBLIOGRAPHY

First Tacoma Narrows Bridge Construction

Eldridge, Clark H. "The Tacoma Narrows Suspension Bridge." Pacific Builder and Engineer 46 (6 July 1940): 35-40.

Moisseiff, Leon S. "Growth in Suspension Bridge Knowledge." Engineering News-Record 123 (17 August 1939): 206-09.

Murrow, Lacey V. "Construction Starts on the Narrows Bridge." Pacific Builder and Engineer 45 (4 March 1939): 34-37.

Neill, Thomas W. "Two New Washington Bridges that Write History." Washington Motorist 21 (July 1940): 4-5, 12.

Official Opening: Tacoma Narrows Bridge and McChord Field, June 30--July 4, 1940, A. D. Dedication Program. Tacoma: Johnson-Cox Company.

"Pacific Northwest Bridges Completed." Engineering News-Record 125 (11 July 1940): 2.

"Puget Sound Bridge Proposed." Engineering News Record 110 (2 February 1933): 171.

First Tacoma Narrows Bridge Destruction

"Action of 'Karman Vortices'." letter to the editor by Blake D. Mills. Engineering News-Record 125 (19 December 1940): 808.

"Another Consultant Board Named for Tacoma Span." Engineering News-Record 12 5 (5 December 1940): 735 .

Averill, Walter A. "Collapse of the Tacoma Narrows Bridge." Pacific Builder and Engineer 46 (December 1940): 20-27.

"Board Named to Study Tacoma Bridge Collapse." Engineering News Record 125 (28 November 1940): 725 .

Bowers, N.A. "Model Tests Showed Aerodynamic Instability of Tacoma Narrows Bridge." Engineering News-Record 125 (21 November 1940)

"Details of Damage to Tacoma Narrows Bridge." Engineering News Record 125 (18 November 1940): 720.

"Dynamic Stability of Suspension Bridges." editorial. Pacific Builder and Engineer 46 (December 1940): [1].

"Dynamic Wind Destruction." editorial. Engineering News-Record 125 (21 November 1940): 672-73.

Eldridge, Clark H. "Tacoma Narrows Bridge: Final Report on Design and Construction." TMs. [1941]

Farquharson, F. B., et al. "A Dynamic Model for the Tacoma Narrows Suspension Bridge. Seattle: University of Washington, 1940.

Frazer, R. A. "Aerodynamic Oscillations of Suspension Bridges." Engineering [London] 171 (2 March 1951): 270-71.

"Film Showing Collapse of Tacoma Span Available." Engineering News-Record 125 (5 December 1940): 733.

"Laboratory Studies on the Tacoma Narrows Bridge at the University of Washington." [Seattle: University of Washington, Department of Civil Engineering, 1941]

"Resonance Effects of Wind." letter to the editor by H. R. Thayer Engineering News-Record 125 (19 December 1940): 808

Steinman, D. B. "Aerodynamic Theory of Bridge-Oscillations." Proceedings of the American Society of Civil Engineers 75 (October 1949): 1147 ff.

"Supplemental Tests on the Dynamic Model of the Original Tacoma Narrows Bridge." [Seattle]: University of Washington, Structural Research Laboratory [1943].

"Tacoma Bridge Oscillations Being Studied by Model." Engineering News-Record 125 (1 August 1940): 139.

"Tacoma Narrows Bridge Wrecked by Wind." Engineering News-Record 125 (14 November 1940): 647, 656-58.

"Tacoma Narrows Collapse." letters to the editor by T.C. Rathbone, C. A. P. Turner, and Harold E. Wessman. Engineering News-Record 125 (5 December 1940): 736-37.

<u>Second Tacoma Narrows Bridge Construction</u>

Ammann, O.H., Charles A. Ellis, and F. H. Frankland. "Unusual Design Problems--Second Tacoma Narrows Bridge." Discussion. Proceedings of the American Society for Civil Engineers 74 (June 1948): 985-92.

Andrew, Charles E. "Tacoma Narrows Bridge Number II . . . The Nation's First Suspension Bridge Designed to be Aerodynamically Stable." Pacific Builder and Engineer 56 (October 1950): 54-56 ff.

_________. Final Report on Tacoma Narrows Bridge, Tacoma, Washington [Washington Toll Bridge Authority], 1952.

_________. "Unusual Design Problems--Second Tacoma Narrows Bridge." Paper. Proceedings of the American Society of Civil Engineers 73 (December 1947): 1483-97.

_________. "Unusual Design Problems--Second Tacoma Narrows Bridge." Discussion. Proceedings of the American Society of Civil Engineers 75 (June 1949): 823-24.

Andrew, Charles E., John I. Purcel, Glenn B. Woodruff, and Theodore von Karman. "The Redesign of the Tacoma Narrows Bridge." Tms. Washington Toll Bridge Authority Consulting Board. 194S, revised 1947.

"Bridge Which Buckled in Wind Will Grow Into Wider Span." Christian Science Monitor, 11 September 1948.

"Cable Spinning at Tacoma Narrows." Engineering News-Record 144 (16 February 1950): 44-4S.

"High-Strength, Lightweight Deck for New Tacoma Narrows Bridge." Engineering News Record 146 (11 January 1951): 34.

Hills, Harold W. "The Techniques of Cable Spinning as Exemplified at the New Tacoma Narrows Bridge." Western Construction 57 (February 1951): 78-81.

Horwood, Ed. "Cable Spinning Operations Underway at Tacoma Narrows Bridge." Pacific Builder and Engineer 55 (November 1949): 44-47.

"'Jinx' Bridge Going Up Again." Western Construction News 24 (15 August 1949): 61-63.

MacPhersan, A. R. "Construction Begins on New Tacoma Narrows Bridge." Roads and Streets 92 (January 1949): 63-65.

"Narrows Bridge Ready Sept. 1950." Seattle Times, 13 March 1948.

"Plywood Plays Vital Role in Building Huge New Tacoma Narrows Suspension Bridge." Veneers and Plywood 44 (September 195O): 26-27.

Souvenir of Tacoma Narrows Bridge, Tacoma, Washington. dedication program. Tacoma, WA: Pioneer Incorporated [1952]

Tacoma Narrows Bridge. brochure. Washington Toll Bridge Authority: [l952]. copy in Washington History File, Washington State Library, Olympia.

"Tacoma Narrows Bridge: Reconstruction to Follow Design Resulting from Extensive Wind Tunnel Research." Roads and Streets 90 (December 1947): 88-90.

"Toll Bridges and Ferries: Tacoma Narrows Bridge." Washington State Highway Commission First Biennial Report; Washington Department of Highways Twenty-fourth Biennial Report, 1950 1952. Olympia: State Printing Plant [1952], 63-64.

University of Washington Structural Research Laboratory tF. B. Farquharson, et al.]. Aerodynamic Stability of Suspension Bridges with Special Reference to the Tacoma Narrows Bridge. Seattle: University of Washington Press, 1954.

Vincent, George S. "Suspension Bridge Vibration Formulas." Engineering News-Record 146 (11 January 1951): 32-34.

Vogel, Elmer C. "New Tacoma Narrows Bridge Called Forerunner of New, Safe Type of Suspension Structure." Seattle Times, 8 October 1950.

<u>Second Tacoma Narrows Bridge Toll Free</u>

"Ceremony Tomorrow to Celebrate Narrows Bridge as Toll-Free Span." Seattle Times, 13 May 1965.

Cunningham, Ross. "Western Sound Area Just as Entitled to Free Bridges as Rest of State." Seattle Times, 9 December 1962.

"End of Tolls Sought for Narrows Span." Seattle Times, 26 March 1964, 1.

"House Unit Would Halt Narrows Tolls." Seattle-Times, 13 February 1965, 9.

"Narrows Bridge Toll Removal Sought in Court." Olympia Daily Olympian, 26 March 1964, 6.

"Narrows Bridge Tolls to Stay." Olympia Daily Olympian, 6 February 1963, 6.

"Narrows Bridge Top Money-maker." Daily Olympian (Olympia), 15 January 1964, 22.

Charles E. Andrew. Engineer

"C. E. Andrew, Span Designer, Dies at 84." Seattle Times, 5 July 1969, 10.

Cunningham, Ross. Unfair to Make Him Scapegoat." Seattle Times, 8 June 1979, A13, in Washington History File, Washington State Library, Olympia.

"Designer of Floating Bridge Succumbs." Olympia Daily Olympian, 6 July 1969, 11, in Washington History File, Washington State Library, Olympia.

Modern Accounts of First Tacoma Narrows Bridge

Berreby, David. "The Great Bridge Controversy." Discover, February 1992, 26-33.

Coatsworth, Leonard. "TNT Staffer Cheats Death in Bridge Collapse." Tacoma News Tribune, 1 July 1976.

"Galloping Gertie--Going--GONE!" Seattle Times, 1 November 1970.

Gunns, Albert F. "The First Tacoma Narrows Bridge: A Brief History of Galloping Gertie." Pacific Northwest Quarterly 72 (October 1981): 162-69.

Helsel, Dorris. "Longtime Bridge Engineer Recalls 'Galloping Gertie with Heartache." Olympia Daily Olympian, 3 September 1986, 1, 2.

"Remember the Death 'Galloping Gertie'?" Seattle Times, 5 November 1964, 39.

Ryan, Jack. "Gertie Isn't Dead Yet: 'Galloper' Has Life in Deep." Seattle Post-Intelligencer, 14 May 1973.

Schultz, Gordon. "Galloping Gertie's Anniversary." Seattle Post-Intelligencer, 7 November 1965

Stansfield, Dick. "'Galloping Gertie' Went Into Narrows 25 Years Ago." Olympia Daily Olympian, 6 November 1967, 15.

"Tacoma Narrows Bridge Tolls Reduces." Engineering News-Record 125 (8 August 1940): 197.

Miscellaneous

Arvid Grant Associates. "Tacoma Narrows Bridge Condition, 1983." For the Washington State Department of Transportation.

_________. "Tacoma Narrows Bridge Report, August 1991." For the Washington State Department of Transportation.

Bleich, Friederich, Conde B. McCullough, Richard Rosencrans, and George S. Vincent. The Mathematical Theory of Vibration in Suspension Bridges. Bureau of Public Roads. Department of Commerce. Washington, DC: Government Printing Office, 1950.

Brierley-Green, David, professional engineer with Arvid Grant Associates Inc., Olympia, WA. Interview by Robert W. Hadlow and Karl W. Stumpf. 20 July 1993. notes.

Gotchy, Joe. Bridging the Narrows. Edited by Gladys C. Para. Gig Harbor, WA: The Peninsula Historical Society, 1990.

Hadlow, Robert W. "Conde B. McCullough, 1887-1946: Master Bridge Builder of the Pacific Northwest." Ph.D. diss. Washington State University, 1993.

[Krier, Robert H.] "Tacoma Narrows Bridge, Historic Bridge Inventory Second Phase, Preliminary Evaluation." Bridge No. 16/110. Washington State Department of Transportation, Olympia, WA. 1993.

McCullough, Conde B., Glenn S. Paxson, and Richard Rosencrans. The Experimental Verification Theory for Suspension Bridge Analysis (Fourier-series Method). Technical Bulletin No. 15. Salem, OR: Oregon State Highway Department, 1942.

McCullough, Conde B., Glenn S. Paxson, and Dexter R. Smith. The Derivation of Design Constraints for Suspension Bridge Analysis (Fourier-series Method). Technical Bulletin No.14. Salem, OR: Oregon State Highway Department, 1940.

McCullough, Conde B., Glenn S. Paxson, and Dexter R. Smith. An Economic Analysis of Short-span Suspension Bridges for . Modern Highway Loadings. Technical Bulletin No. 11. Salem, OR: Oregon State Highway Department, 1938.

McCullough, Conde B., Glenn S. Paxson, and Dexter R. Smith. Rational Design Methods for Short-span Suspension Bridges for Modern Highway Loadings. Technical BuIletin No. 13. Salem, OR: Oregon State Highway Department, 1940.

Morgan, Murray and Rosa Morgan. South on the Sound: An Illustrated History of Tacoma and Pierce County. Windsor Publications, 1984.

Plowden, David. Bridges: The Spans of North America. New York: W. W. Norton, 1974, 1984.

Steinman, David and Sara Ruth Watson. Bridges and their Builders.; New York: G. P. Putnam's Sons, 1941.

U.S. Department of the Interior. National Park Service. "National Register of Historic Places Nomination Form for Tacoma Narrows Bridge Ruins/Galloping Gertie, Pierce County, Washington. 1992 .

Washington. State Department of Transportation. Bridge Preservation Section. Bridge Files.

APPENDIX

Specifications of Tacoma Narrows bridges

	1st Bridge	2nd Bridge
Total Length	5,939′	5,979′
Suspension section	5,000′	5,000′
Center Span	2,800′	2,800′
Side Spans, each	1,100′	1,100′
East Approach and anchorage	345′	365′
West Approach and anchorage	594′	614′
Center Span height above water	195′	187.5′
Width of Roadway	26′	49′ 10"
Width of Sidewalks, each	5′	3′ 10"
Diameter of Main Suspension Cable	17-1/2"	20-1/4"
Weight of Main Suspension Cable	3,817 T	5,441 T
Weight Sustained by Cables	11,250 T	18,160 T
Number of #6 Wires per Cable	6,308	8,705
Weight of Shore Anchors	52,500 T	66,000 T
Tower Dimensions:		
Height Above Piers	425′	467′
Weight of Each Tower	1,927 T	2,675 T
Piers:		
Area	118′-11"x 65′-11"	119′ x 66′
East Pier, Total Height	247′	265′
Weight		65,000 T
Depth of Water	120′	135′
Bottom Penetration	105′	90′
West Pier, Total Height	198′	215′

Weight		52,000 T
Depth of Water	120′	120′
Bottom Penetration	55′	55′

Source: Joe Gotchy, *Bridging the Narrows*, edited by Gladys C. Para, (Gig Harbor, WA: The Peninsula Historical Society, 1990),97. Gotchy wrote the depth of water and penetration figures for the east pier became public information at the first bridge's completion, but an undated *Tacoma News Tribune*, in his possession gave the figures for the first bridge that appear in this table. Charles E. Andrew was the source for the figures for the second bridge.

ENDNOTES

1. Murray and Roas Morgan, South on the South Shore: An Illustrated History of Tacoma and Pierce County (Windsor Publications, 1984): 115; see also, Albert F. Gunns, "The First Tacoma Narrows Bridge: A Brief History of Galloping Gertie," Pacific Northwest Quarterly 72 (October 1982): 165-66.

2. Morgan and Morgan, South on the Sound, 116; "Puget Sound Bridge Proposed," Engineering News-Record 110 (2 February 1933): 171; the design for Chandler's 1,200' structure with a 196' clearance is unknown; Gunn, "The First Tacoma Narrows Bridge," 166-67.

3. Gunn, "The First Tacoma Narrows Bridge," 166-67; "Construction Starts on the Narrows Bridge," Pacific Builder and Engineer 45 (4 march 1939): 34-35.

4. Dorris Hensel, "Longtime Bridge Engineer Recalls 'Galloping Gertie' with Heartache," Daily Olympian (Olympia, WA), 3 September 1986, 1, 2; Joe Gotchy, Bridging the Gap, edited by Gladys C. Para, (Gig Harbor, WA: The Peninsula Historical Society, 1990), 41-42.

5. Official Opening: Tacoma Narrows Bridge and McChord Field, June 30--July 4, 194a, A. D. Dedication Program. Tacoma: Johnson Cox Company), 16; "Construction Starts on the Narrows Bridge," Pacific Builder and Engineer 45 (4 March 1939): 34-35; Charles E. Andrew, Final Report on Tacoma Narrows Bridge, Tacoma, Washington, [Washington Toll Bridge Authority] 1952, 13-14.

6. For a comparison of dimensions between the first and second Tacoma Narrows Bridge, see Gotchy, Bridging the Narrows, 97.

7. Leon S. Moisseiff, "Growth in Suspension Bridge Knowledge," Engineering News-Record 123 (17 August 1939): 206-09, 206 and 208 (quotes).

8. Ibid., 207-08

9. Ibid., 208-09.

10. Eldridge, Clark H., The Tacoma Narrows Suspension Bridge," Pacific Builder and Engineer 46 (6 July 1940): 35.

11. Neill, Thomas W., "Two New Washington Bridges that Write History," Washington Motorist 21 (July 1940), 4-5, 12; Gotchy, Bridging the Gap, 39; "Galloping Gertie--Going--GONE!" Seattle Times, 1 November 1970; "Tacoma Bridge Oscillations Being Studied by Model," Engineering News-Record, 125 (1 August 1940): 139.

12. "Tacoma Bridge Oscillations Being Studied by Model," 35; "Laboratory Studies on the Tacoma Narrows Bridge at the University of Washington." [Seattle: University of Washington, Department of Civil Engineering, 1941] [xii]; Friederich Bleich, Conde B. McCullough, Richard Rosencrans, and Georqe S. Vincent, The Mathematical Theory of Vibration in Suspension Bridges, Bureau of Public Roads, Department of Commerce, (Washington, DC: Government Printing Office, 1950), 7-8; Matthys Levy and Mario Salvadori in Why Buildings Fall Down: How Structures Fail (New York W. W. Norton, 1993), 110-11, suggest that the dampers or hydraulic shocks never functioned properly because sandblasting grit used on the steel girders prior to painting damaged their leather seals, rendering them useless; N. A. Bowers, "Model Tests Showed Aerodynamic Instability of Tacoma Narrows Bridge," Engineering News-Record 125 (21 November 1940): 44.

13. Levy and Salvadori, Why Buildings Fall Down, 111; Bower, "Model Tests Showed Aerodynamic Instability of Tacoma Narrows Span," 44-47; "Galloping Gertie--Going--GONE!"; Walter A. Averill, "Collapse of the Tacoma Narrows Bridge," Pacific Builder and Engineer 46 (December 1940): 20-27.

14. N. A. Bowers, "Tacoma Narrows Bridge Wrecked by Wind," Engineering News-Record 125 (14 November 1940): 647, 656, 658; Levy and Salvadori, Why Buildings Fall Down, 113-14; Averill, "Collapse of the Tacoma Narrows Bridge," 20-26, David Steinman and Sara Ruth Watson, Bridges and their Builders (New York: G. P. Putnam's Sons, 1941), 355-57, 356 (quote).

15. Averill, "Collapse of the Tacoma Narrows Bridge," 20-26; Levy and Salvadori, Why Buildings Fall Down, 113-14; The Mathematical Theory of Vibration in Suspension Bridges, 7-11; Steinman and Watson, Bridges and their Builders, 357 (quote). Both the Seattle Times and the Seattle Post-Intelligencer issues for the week after the disaster give much coverage to the bridge failure.

16. Dynamic Wind Destruction," editorial, Engineering News Record 125 (21 November 1940): 672; Bleich, McCullough, Rosecrans, and Vincent, The Mathematical Theory of Vibration in Suspension Bridges, 7-11. The state of Washington's investigation board members were Lief Sverdrup, senior partner of Sverdrup and Parcel, consulting engineers of St. Louis; Russell Cone, resident and later chief engineer of Golden Gate Bridge project; and Francis Donaldson, consulting engineer, chief engineer in early stages of Grand Coulee Dam project. The PWA's board consisted of Glenn Woodruff, detail design engineer for the San Francisco-Oakland Bay Bridge; Theodore von Rarman, aeronautical engineer and director of the David Guggenheim Aeronautical Institute at the California Institute of Technology; and Othmar Ammann, engineer involved in the design and construction of the Hell Gate, Triborough, and Bronx-Whitestone bridges in New York, and member of the board of engineers in charge of the Golden Gate Bridge construction. It budgeted $2.8 million for the project. See "Board Named to Study Tacoma Bridge Collapse," Engineering News-Record 125 (28 November 1940): 725; "Another Consultant Board Named for Tacoma Span," Engineering News-Record 125 (5 December 1940): 735; and Averill, "Collapse of the Tacoma Narrows Bridge," 26-27; "Tacoma Narrows Bridge: Reconstruction to Follow Design Resulting from Extensive Wind Tunnel Research," Roads and Streets 90 (December 1947): 72-73, 90

17. Levy and Salvadori, Why Buildings Fall Down, 116-19; Steinman and Watson, Bridges and Their Builders, 360, 363.

18. Steinman and Watson, Bridges and Their Builders, 359-60, 363 (quote); Levy and Salvadori, Why Buildings Fall Down, 117-18.

19. Gunns, "The First Tacoma Narrows Bridge," 165, 168-69.

20. Ibid., 168; Andrew, Final Report on the Tacoma Narrows Bridge, 14; Levy and Salvadori mentioned the early 1990s research that confirmed Theodore von Xarman's conclusions, but they did not disclose the source. See Levy and Salvadori, Why Buildings Fall Down, 118.

21. Levy and Salvadori, Why Buildings Fall Down, 119. According to Dayid Plowden, in Bridges: The Spans of North America, the Tacoma Narrows Bridge disaster ended Moissieff's career. He had submitted a plan in 1938 for bridging the Straits of Mackinac. Confident in his design for the Narrows structure, he submitted a proposal for a 4,600' span with identical features. David Steinman

and Glenn Woodruff finally were awarded the contract for an 8,614' structure with a 3,800' main span. Its 38'-deep stiffening trusses were 68 percent greater in span length-to-stiffening truss than those found on the Golden Gate Bridge. Steinman and Woodruff's design, Plowden wrote "was probably the most aerodynamically stable suspension bridge ever built. " See Plowden, 291.

22. Andrew, Final Report of the Tacoma Narrows Bridge, 18-19; Andrew, "Unusual Design Problems--Second Tacoma Narrows Bridge," paper, Proceedings of the American Society of Civil Engineers 73 (December 1947): 1483-97.

23. McCullough wrote in the late 1930s and early I940s that suspension bridges were a practical alternative for short crossings because more sophisticated mathematical calculations, using the Fourier-series or sine-series method of exact stress analysis, gave more accurate calculations than the traditional and less reliable elastic theory. It streamlined the designer's approach to determining a structure's specifications based on load requirements, roadway widths, and total length. The Fourier-series method was a short-cut because using it saved time, thus keeping down costs down and making suspension bridges economical for short crossings. See Robert W. Hadlow, "Conde B. McCullough, 1887-1946: Master Bridge Builder of the Pacific Northwest," (Ph.D. diss., Washington State University, 1993), 77-79, 191, 216-17. See also Conde B. McCullough, Glenn S. Paxson, and Dexter R. Smith, An Economic Analysis of Short-span Suspension Bridges for Modern Highway Loadings, Technical Bulletin No. 11 (Salem, OR: Oregon State Highway Department [OSHD], 1938); and McCullough, Paxson, and Smith, Rational Design Methods for Short-span Suspension Bridges for Modern Highway Loadings, Technical Bulletin No. 13 (Salem, OR: OSHD, 1940); McCullough, Paxson, Smith, The Derivation of Design Constraints for Suspension Bridge Analysis (Fourier-series Method), Technical Bulletin No. 14 (Salem, OR: OSHD, 1940); and McCullough, Paxson, and Richard Rosencrans, The Experimental Verification Theory for Suspension Bridge Analysis (Fourier-series Method), Technical Bulletin No. 15 (Salem, OR: OSHD, 1942).

24. Andrew, Final Report of the Tacoma Narrows Bridge, 18-19, 32-38; Charles E. Andrew, "Unusual Design Problems--Second Tacoma Narrows Bridge, "paper, Proceedings of the American Society of Civil Engineers 73 December 1947): 1483-97.

25. Andrew, "Unusual Design Problems--Second Tacoma Narrows Bridge," 1490-91.

26. Ibid., 1491-92; Andrew, Final Report of the Tacoma Narrows Bridge, 81-83 and fig. 12.

27. Andrew, Final Report of the Tacoma Narrows Bridge, 22-23; Andrew, "Unusual Design Problems--Second Tacoma Narrows Bridge," 1492-94.

28. "'Jinx' Bridge Going Up Again," Western Construction News 24 (15 August 1949): 61-63; contracts for new structure exclusive of reused west approach spans and anchors blocks was $11,196,584.19. The main contracts were: $8,263,902.92 to Bethlehem Pacific Coast Steel Corporation and $2,932,681,27 to John A. Roebling's Sons. See "Tacoma Narrows Bridge, No. 16/110," Kardex Card File, Bridge Condition Unit, Washington State Department of Transportation, Olympia, WA.

29. Andrew, Final Report of the Tacoma Narrows Bridge, 16-17.

30 Lacey V. Murrow, Construction States on the Narrows Bridge," Pacific Builder and Engineer 45 (4 March 1939): 35-36; Gotchy, Bridging the Narrows, 97.

31. A. R. MacPherson, "Construction Begins on New Tacoma Narrows Bridge, "Roads and Streets 92 (January 1949): 63-64.

32. Creeper derricks erected the tower leges by stacking 32' sections of the columns. The procedure for placing the 28-ton saddles was delayed when a strong earthquake rocked the Puget Sound area in April 1949. Its magnitude was so great that it hurled one of the saddles from its perch and threw it in the Narrows. See Gotchy, Bridging the Narrows, 48, 53; "'Jinx' Bridge Going Up Again, H 61.

33. "'Jinx' Bridge Going Up Again," 61-62; Andrew, Final Report on Tacoma Narrows Bridge, Tacoma, Washington, 21.

34. For a thorough discussion of the cable operation, see Ed Horwood, "Cable Spinning Operations Underway at Tacoma Narrows Bridge," Pacific Builder and Engineer 55 (November 1949): 44-47. See also Gotchy, Bridging the Narrows, 56; and Andrew, Final Report on Tacoma Narrows Bridge, 26.

35. Andrew, Final Report on Tacoma Narrows Bridge, 30.

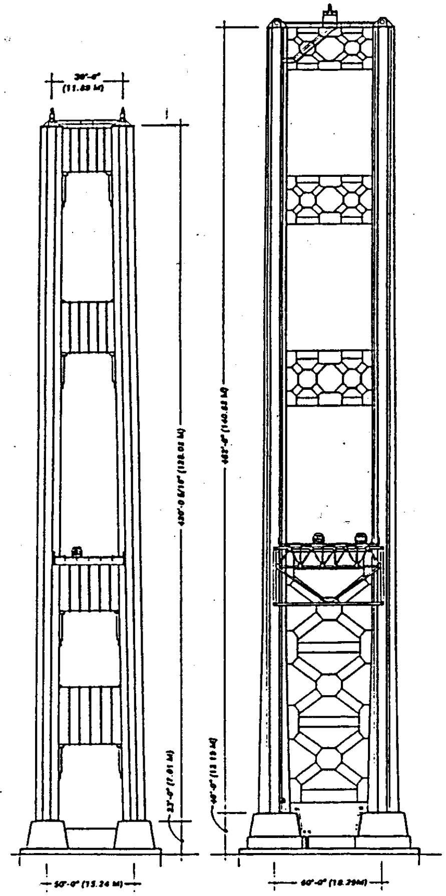
36. Gotchy, Bridging the Narrows, 64, 80; Andrew, Final Report on Tacoma Narrows Bridge, 31

37. "Ceremony Tomorrow to Celebrate Narrows Bridge as Toll-Free Span," Seattle Times, 13 May 1965, 4.

38. Arvid Grant Associates, "Tacoma Narrows Bridge Report, August l991," for the Washington State Department of Transportation, 6-7.

40. Ibid., 1-4, 104-09.

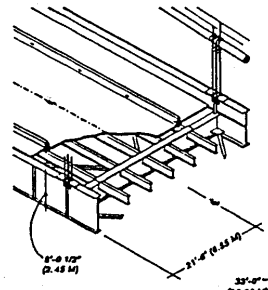
41. Arvid Grant Associates, "Tacoma Narrows Bridge Report, August 1991," for the Washington State Department of Transportation, 6-7.



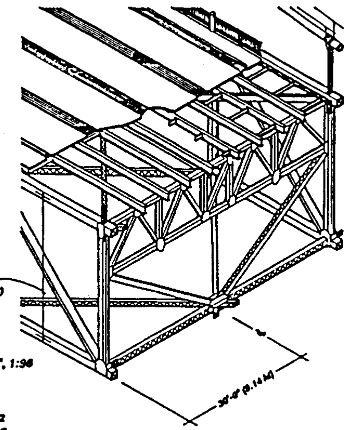
1940 Bridge Scale: 1" = 20', 1:240 1950 Bridge

The towers of the 1940 bridge accomodated a two-lane road deck. Tower legs for the 1950 bridge were designed for a four-lane road deck. Wider pier pedestals were erected for the new tower legs. They were also lengthened 18 feet to raise the tower steel above the Narrows' corrosive salt water.

Tower Elevations



1940 Bridge Roadway



1950 Bridge Roadway

Axonometrics Scale: 1/8" = 1'-0", 1:96

The Tacoma Narrows Bridge collapsed on 7 November 1940 during a gale between 35 to 42 miles per hour, with a wind pressure of only five pounds per square foot. The steady wind's effects on the structure produced a fluctuating resultant force that synchronized in timing and direction with the bridge's natural harmonic motions (figs. 1&2), progressively amplifying them to destructive levels. Both vertical and torsional oscillations contributed to the failure of the bridge. The bridge's inherent weakness and susceptibility to these winds lay in its shallow stiffening girders and its narrow roadway.

Theodore von Karman, who had pioneered wind tunnel analysis at the California Institute of Technology, argued that the bridge deck's aerodynamic shape was a more important factor in its failure than its lightness and flexibility. Von Karman suspected that the bridge had experienced vortex shedding, a condition where objects like airplane wings or bridge decks displace air flowing around them and form eddies or vortices, which may induce vibration in the object (figs 3&4). He believed that wind flowing over the bridge's solid girder side plates created shedding that when combined with the flutter and resonance already present in the deck produced the violent oscillations that caused the catastrophic failure (figs. 5&6).

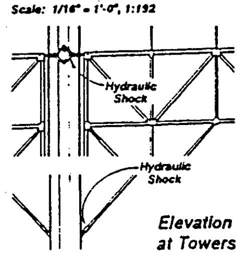
Designing the replacement bridge's deck stiffening system involved subjecting dynamic scale models to wind tunnel testing to better understand wind effects on them.

Designers for the 1950 bridge were not satisfied with their ability to eliminate torsional and vertical movements in their proposed structure. They hoped to enhance their design's natural damping ability with mechanical devices. One of these was a double-lateral bracing system in the stiffening truss. It increased torsional frequency motion and tortional stiffness.

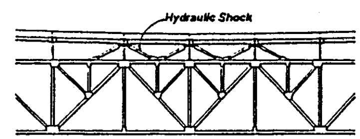
Damping Mechanism

1950 Bridge

Scale: 1/16" = 1'-0", 1:192



Elevation at Towers

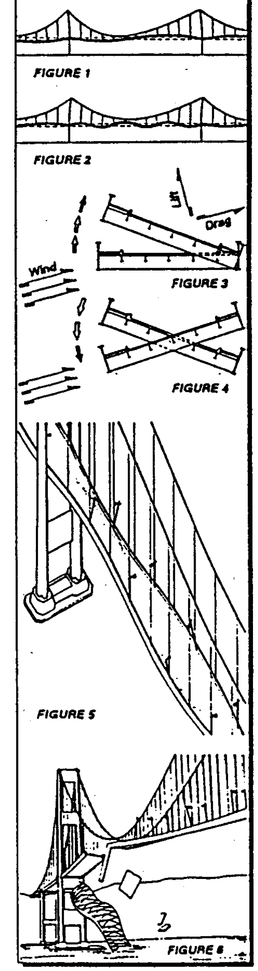


Elevation at Mid-Span

To eliminate torsional and vertical movement cylindrical hydraulic shock absorbers were used at three points on the bridge: coupling the top of the stiffening truss at mid-span with the suspension cables, connecting between the top chords of the main span and side span stiffening trusses, and extending as outriggers from the trusses' bottom chords to the towers.

1940 Bridge Failure

Diagrams & Illustrations



TACOMA NARROWS BRIDGE - 1950

STATE ROUTE 16 SPANNING THE NARROWS

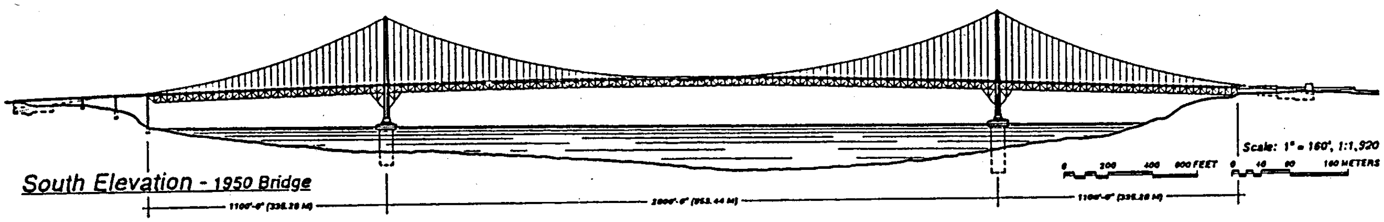
PIERCE COUNTY

TACOMA

WASHINGTON

WA-99

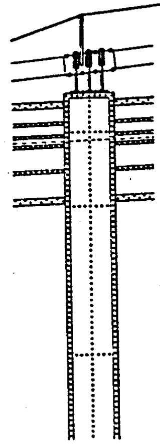
WASHINGTON STATE BRIDGES RECORDING PROJECT



South Elevation - 1950 Bridge

TACOMA NARROWS BRIDGE

1940 TACOMA, WASHINGTON 1950



Detail

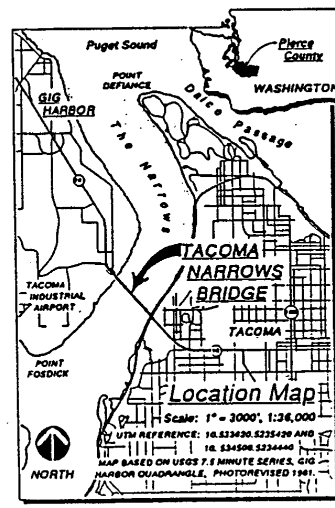
Hold Down Ropes at Tower No. 3 - 1940 Bridge

Scale: 3/8" = 1'-0", 1:32

The Washington Toll Bridge Authority built the 5,000-foot, $14 million Tacoma Narrows Bridge in 1950 to replace a previous structure, designed by the respected engineer Leon S. Moisseiff, that collapsed in 1940 from aerodynamic instability. Like its predecessor, it was the world's third longest suspension bridge, behind only the Golden Gate and the George Washington bridge for length of suspended span. But unlike its predecessor, the second Tacoma Narrows Bridge was built with several features that made it unaffected by wind forces. It marked a new beginning for the structural engineering field in this type of construction. Bethlehem Pacific Coast Steel Corporation was the general contractor. John A. Roebling's Sons Co. supplied the cable work.

University of Washington structural engineers directed by F. B. Farquharson attempted to understand the first structure's flaws through wind tunnel testing of dynamic scale models. They pioneered the field of bridge aerodynamics with the fruits of their research resulting in the design of the second Tacoma Narrows Bridge and other bridges that followed.

Charles E. Andrew and Dexter R. Smith, principal design engineers, incorporated many elements in the new bridge directed at preventing the dangerous twisting and galloping motions that destroyed its predecessor. These included deep open deck trusses, rather than shallow plate girders, that insured greater structural rigidity and, when combined with deck grating between traffic lanes, less wind resistance. A larger roadway width-to-span length increased twisting resistance and reliable damping mechanisms prevented the indefinite progressive increase in aerodynamic oscillation magnitude seen in the earlier bridge.



Location Map

Scale: 1" = 3000', 1:36,000

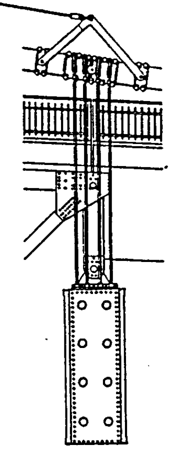
UTM REFERENCE: 10.533430.5235420 AND 10.534506.5234440

MAP BASED ON USGS 7.5 MINUTE SERIES, GIG HARBOR QUADRANGLE, PHOTOREVISED 1981.

This recording project is part of the Historic American Engineering Record (HAER), a long-range program to document historically significant engineering and industrial works in the United States. The HAER program is administered by the Historic American Buildings Survey/Historic American Engineering Record Division (HABS/HAER) of the National Park Service, U.S. Department of the Interior. The Washington State Bridges Recording Project was cosponsored during the summer of 1993 by HABS/HAER under the general direction of Dr. Robert J. Kapsch, Chief, and by the Washington State Department of Transportation (WSDOT), Bernie L. Chaplin, Environmental Program Manager.

The field work, measured drawings, historical reports, and photographs were prepared under the direction of Project Leader Eric N. DeLony, Chief of HAER and HAER Historian Dean A.Herrin,Ph.D. The recording team consisted of Supervisory Architect Karl W. Stumpf (University of Illinois at Urbana-Champaign); Supervisory Historian Robert W. Hadlow, Ph.D. (Washington State University); Architects Vivian Chi (University of Maryland), Erin M. Doherty (Miami University), Catherine I. Kudlik (The Catholic University of America) and Wolfgang G. Mayr (US/ICOMOS, Technical University of Vienna, Austria); Historians Jonathan C. Clarke (US/ICOMOS, Ironbridge Institute, England) and Wm. Michael Lawrence (University of Illinois at Urbana-Champaign). Formal photography was done by HAER Photographer Jet Lowe. WSDOT Cultural Resources Specialist Elizabeth A. Robbins served as department liaison.

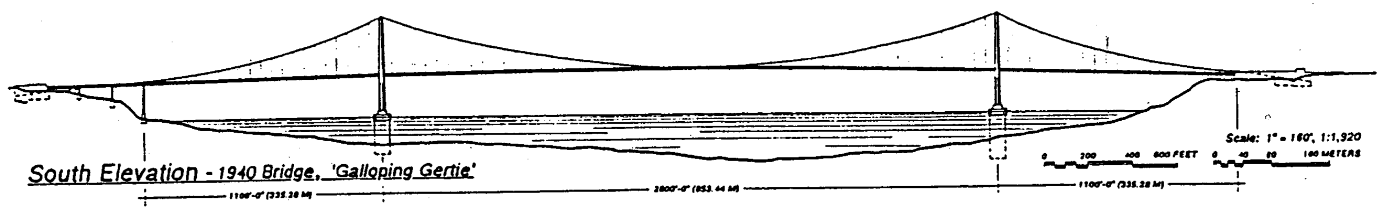
Drawings were developed from construction documents of the 1940 and 1950 bridges located in WSDOT files and field measurments.



Detail

Hold Down Cables at Tower No. 3 - 1950 Bridge

Scale: 3/8" = 1'-0", 1:32



South Elevation - 1940 Bridge, 'Galloping Gertie'

Karl W. Stumpf and Wolfgang G. Mayr, Summer 1993

TACOMA NARROWS BRIDGE - 1950

WASHINGTON STATE BRIDGES RECORDING PROJECT

TACOMA

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